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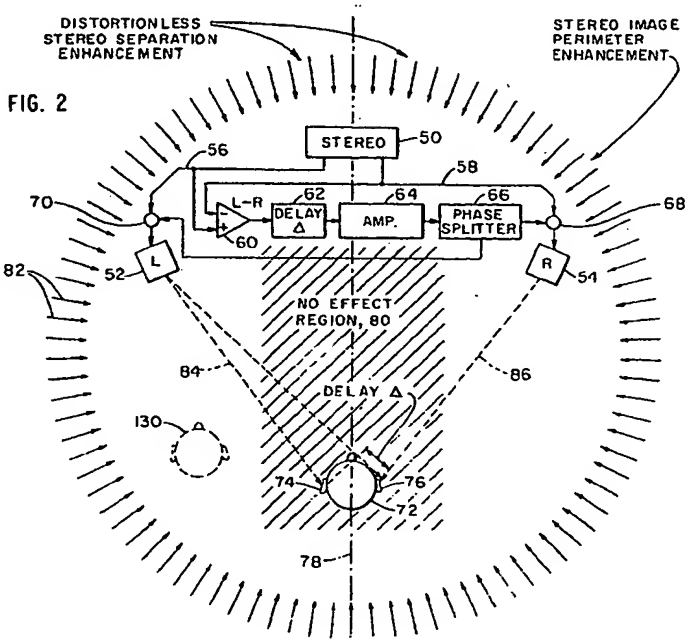
(54) Stereophonic audio reproduction system

(57) A stereo enhancement system employs a difference signal L-R derived at 60 from the left and right stereo channels in which the difference signal is delayed 62, amplified 64, and then subtractively combined 68, 70 with the appropriate channel signals to cancel left/right speaker mixing at the listener's ears, thereby to improve stereo separation without centre region distortion. Depending on the amplification level of the difference signal, an increase in the perimeter sound over that produced at the central region gives a "wrap around" effect with only two speakers by increasing the volume of only the left/right directional sound components relative to centrally located sounds which have no left/right directionality. In order to compensate for the angle between the listener and the speakers, a continuously variable delay is provided in the $10^{-3} - 10^{-4}$ seconds range by the use of a serial-analog delay bucket brigade device. Ultrashort delays can be created by using equal initial delays in the left and right stereo channels. The difference signal is then delayed by an amount equal to either of the two initial delays plus the amount of desired delay. When serial analog delay devices are utilized, the clock rate of the delay line used for the difference signal is made slightly lower than the clock rate of the delay lines used in initially delaying the left/right signals, thereby to provide for ultrashort delayed difference signals. Off-centre listener positions are accomodated by a further continuously variable delay line in one or the other of the left and right channels.

FIG. 2



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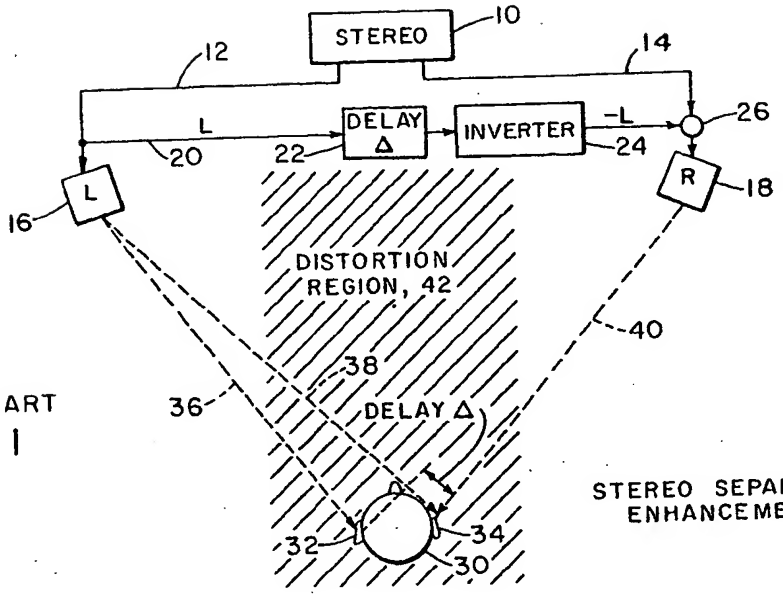
The drawings originally filed were informal and the print here reproduced is taken from a later filed formal copy.



PRIOR ART
FIG. 1

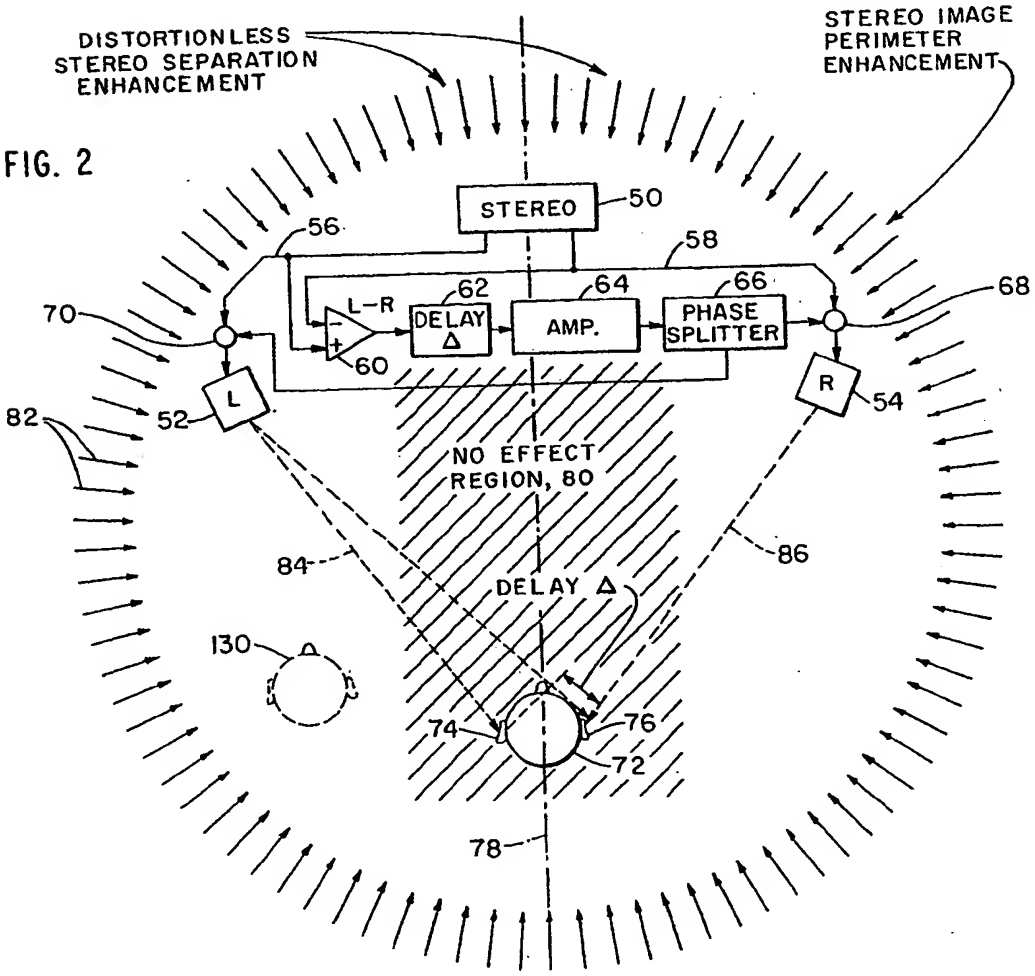


FIG. 2

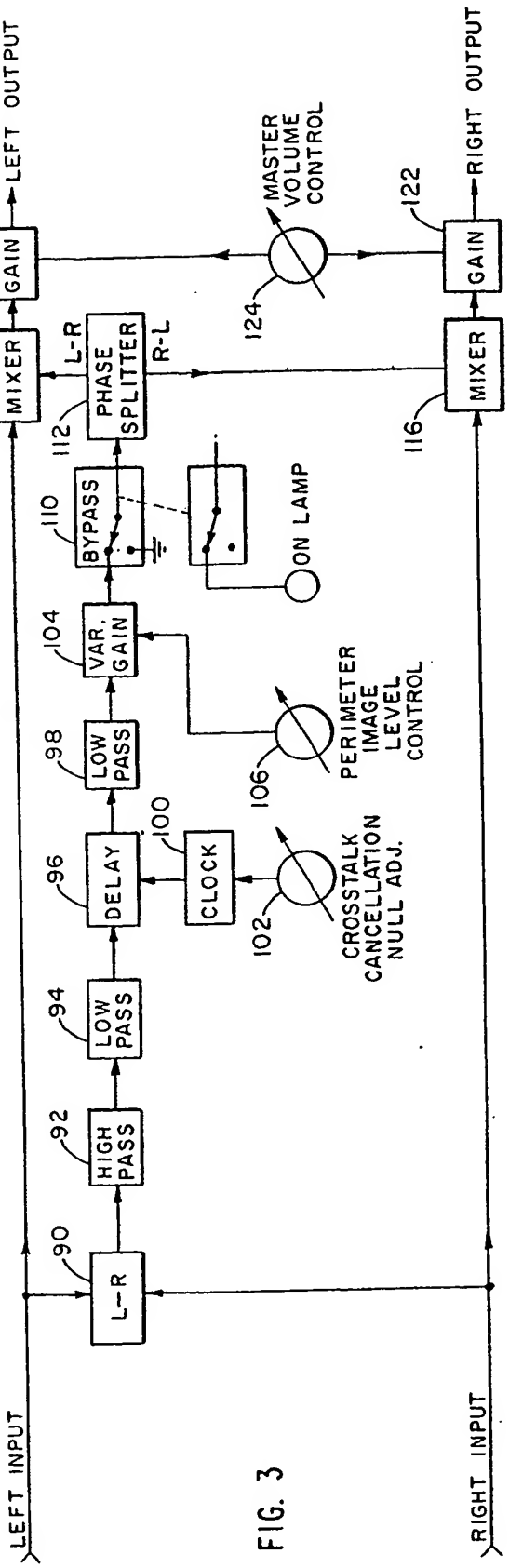


FIG. 3

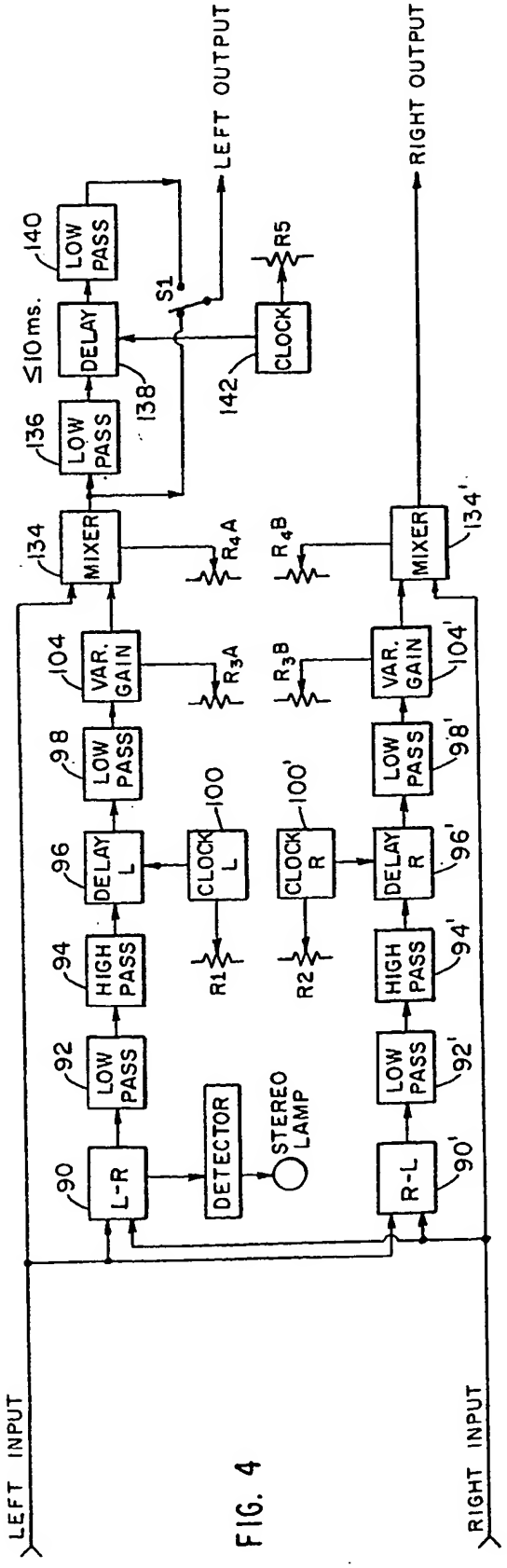
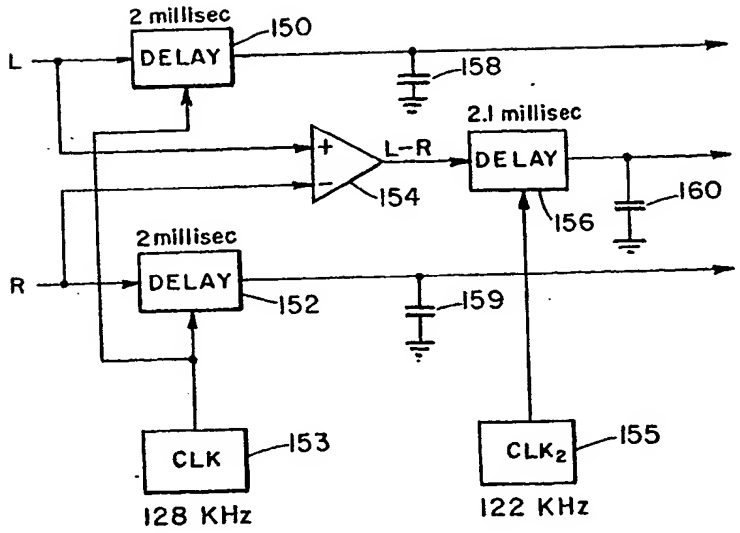


FIG. 4

FIG. 5



SPECIFICATION

Apparatus for a stereophonic audio reproduction system

This invention relates to stereo reproduction techniques and more particularly to a method and apparatus for improving stereo separation or enhancing peripheral sounds or both.

Previously, complete separation of stereo signals has been achieved by using head phones in which a left channel of a stereo reproduction system is applied to the left ear phone and the right channel is applied to the right ear phone. Although in 1960 Benjamin Bauer described an attempt to make head phones sound more like loudspeakers by simulating the delayed leakage of the left speaker output to the right ear of a listener and vice versa, until recently there has been very little development towards stereo separation for loudspeakers.

There is a certain amount of mixing of sounds from a pair of left and right loudspeakers at a listeners's ear due to the fact that sounds from that speaker nearer the listener's left ear will travel to each speaker, sound arriving at the left ear before sound arriving at the right ear, which is further from the speaker than is the left ear. The sounds which arrive at the right ear are mixed with sounds arriving at the right ear from the speaker nearer the right ear. Thus the separation which was initially established by virtue of recording techniques on a record or tape is in some sense destroyed since each ear can hear sounds produced by both of the stereo speakers.

When Bauer proposed making headphones sound more like loudspeakers, he also proposed the reverse; i.e. that it would be possible to cancel stereo mixing when using loudspeakers and that this would give loudpseakers a similar separation to that of headphones.

Subsequent work on stereo loudspeaker separation was done in Germany by Damaske et al. In their system, signal arriving at the right ear is delayed by the transit time for the sound to cross the listener's face to the left ear. This delayed signal is then frequency contoured, inverted and added to the left speaker signal and this correction signal in the left speaker is then used to acoustically cancel out the right speaker leakage at the left ear. The same is done between the left and right channels such that acoustic cross-talk between the ears is cancelled.

One of the basic difficulties with delaying the left channel and right channel speaker signals is that there is a broad central region between the channels in which there is a "muddying" effect i.e. a frequency distortion. This effect is due to the use of full and left and right channel signals. In the central region no left/right i.e. direction information exists and the signal is essentially monaural and as a result, not only is there frequency distortion, but also volume attenuation. The frequency distortion is due to a "comb filtering effect" in which the levels of various frequency components are increased or decreased in the central region and the clarity and fidelity of the original recording is lost for sound produced from [illegible] region.

In most recordings the important sound producing instruments or performers create their sound in a central region between microphones. Thus the muddying at "centre stage" i.e. in the central region creates significant problems in a stereo reproduction system when utilising the known enhancement technique.

According to the present invention we propose apparatus for a stereophonic audio reproduction system having left and right channel outputs comprising:

means for deriving a difference signal from signals in said left and right channels;

means for delaying said difference signal; and

a phase splitter coupled to said delay means for phase splitting said delayed signal and coupling the two phase split phases of delayed signal into said left and right channels so as to subtract delayed left minus right and right minus left components from respectively the left and right channels for enhancing stereo image separation.

Rather than employing the full left and right channel signals, delaying, inverting and then inserting them in the other channel, the system of the present invention achieves separation by employing a left minus right differential signal, delaying it, frequency contouring it, and inserting it into the left channel and its inverse into the right channel. This may be accomplished by feeding the left and right channels to a differential amplifier, the output of which is delayed by a bucket brigade device such as a serial analog delay, which is clocked at the appropriate rate for the required delay. The output of the delay unit is then amplified, and coupled to a phase splitter which inserts right minus left channel signals into the right channel and left minus right channel signals into the left channel. In so doing, sounds which have no left/right directionality, such as those emanating from centre stage, are not delayed or inverted and in fact are not involved. This leaves the central region sounds completely undistorted, with no comb filtering effect being superimposed.

The types of delays which may be produced are ultrashort and of the order of $(1-10)\times10^{-4}$ seconds. These delays are not easily produced. They are produced in the present invention by a serial-analog delay (SAD) such as a bucket brigade device. These delay devices must typically be clocked at about 3×10^{6} Hertz, which is ten times the normal rate, to achieve delays as short as 1×10^{-4} seconds. In order to achieve a further shortness in the acoustic delay or allow use of slower SADs, SADs of equal delay may be inserted into the left and right channels with a third delay used for the differential signal. The third delay may be provided by an SAD which is clocked at a rate slightly lower than the rate at which the delay lines for the non-differential signals are clocked, with the difference in clocking rates determining delays as small as 1×10^{-5} seconds or less.

By using variable clock rates, continuously variable delays may be employed which can compensate for listener postion between the two speakers. This is important since fixed delays will produce the required separation only a a given angle with respect

to each speaker. Rather than a listener having to orient the speakers, a variable delay provides that a listener may provide for maximum stereo separation regardless of his angular relationship to the speakers. The delay may be set by determining the ratio between the distance that separates the two speakers and the distance between the left speaker and the listener's left ear.

For off-centre listening a broad band delay may be used in one channel to compensate for a listener being closer to one of the two speakers.

It has been found, that in addition to achieving excellent separation, a "wrap around" sound can be achieved which is akin to the positioning of numerous, i.e. of the order of one hundred speakers, around the periphery of a room. This effect is achieved with only two loud speakers. In the present invention this is accomplished by amplifying the output of the delay circuit beyond the level required for image separation. What this achieves is as much as a ten dB volume increase in the peripheral sound level over the central sound level, since it is only the left/hand components which are amplified and inserted in this manner. This peripheral enhancement is achieved without centre image distortion and may be varied by the listener according to his own listening requirements.

Further, it has been found that peripheral enhancement is effective to an adequate extent at positions other than the position at which separation enhancement is maximal. Thus, peripheral sound enhancement may be achieved for listeners in the room at different positions, although the separation effect will be diminished for positions at the room's perimeter.

The image separation and peripheral sound enhancement corresponds to speakers capable of projecting sounds at 180 degrees as opposed to the 40-60 degrees of typically placed speakers with respect to the listening position. Thus, in the present invention may be used for apparently spreading the audio source beyond the angle of the loudspeakers toward that of the original sounds with respect to the microphones originally used in the recording. Not only is there a left/right spreading effect, but also there is better spreading of the forward and rear portions of the performance, such that a total immersion in sound is possible with this system.

The present invention does not affect the frequency response of the central image and therefore monaural or centrally located equal volume and phase signals in each channel are not adversely affected.

It will be appreciated that most rumble is produced by the vertical movement of the stylus which corresponds to the left/right signal, while very low frequencies contain no left/right components. By utilizing a high pass filter having a low frequency cut off of approximately 70 Hertz, for the differential signal, rumble which is produced by vertical motion of the stylus in the recording or reproduction of a record is not accentuated in the subject system while bass response is not effected.

Embodiments according to the present invention will now be described by way of example and with reference to the drawings, in which:-

Figure 1 is a diagramatic representation of a prior art system for stereo separation enhancement, indicating a centrally located distortion region;

Figure 2 is a diagramatic representation of a separation and perimeter enhancement system according to the present invention, illustrating diagramatically a perimeter enhancement and distortionaless stereo separation enhancement system;

Figure 3 is a block diagram of one embodiment of the present invention;

Figure 4 is a block diagram of another embodiment of the present invention in which off-centre listening positions may be accommodated; and

Figure 5 is a schematic and block diagram of one embodiment of the present invention in which ultrashort acoustic delays are produced through the employment of a double delay technique.

Referring to Figure 1, in a typical conventional system, a stereo unit 10 which may be a receiver, an amplifier or any similar type of equipment which produces left and right channel signals, is coupled via lines 12 and 14 respectively to left and right speakers 16 and 18. With respect to left channel to right channel cancellation, a line 20 is coupled from the left channel line 12 to a delay unit 22 which delays signals on this line by an amount Δ. The output of delay unit 22 is applied to an inverter 24, the output of which is applied to a mixer or summing point 26.

If the full left channel signal is indicated by the letter L, then the output of the inverter 24 is $-L$.

If a listener 30 is located midway between speaker 16 and 18 i.e. with his left ear 32 nearer the left speaker 16 and his right ear 34 nearer the right speaker 18, then as can be seen from the diagram, sound may reach left ear 32 from speaker 16 along a line 36. Sound from this speaker will also reach right ear 34 along a line 38 as it crosses the face of the listener. The sound trasnmitted to the right ear travels a longer distance than the sound transmitted to the left ear and will be delayed at the right ear by an amount Δ corresponding to the difference in path length between the sound paths to both of the ears.

As can also be seen, sound impinges on right ear 34 from speaker 18 along a path 40 such that there exists at the right ear a certain amount of mixing of left and right channels. This destroys stereo separation to a certain extent.

In order to eliminate such mixing, delay unit 22 and inverter 24 couple an inverted left signal into the right channel so as to exactly cancel the left channel signal at the right ear. Thus at the right ear, a delayed and inverted left channel signal arrives at the same time as the right channel signal, with the delayed inverted left signal cancelling the signal which arrives from the left speaker.

In so doing, a distortion region 42 is created which occupies generally the centre region between the two speakers in which sound in this region is "muddied", that is there is frequency distortion due to a comb filtering effect because the entire left channel signal is inverted, delayed, and mixed with the right channel signal.

It will be appreciated that for cancellation at the

left ear, a reverse type situation is envisaged in which the right channel signal is delayed by Δ, inverted and then coupled into the left channel. Thus the distortion is symetric about a central line between the two speakers.

While stereo separation is in fact enhanced by the system illustrated in Figure 1, signals lacking left/right directionality, will be significantly attenuated and distorted in the central region illustrated.

Referring now to Figure 2, a system is illustrated in which not only is there distortionless stereo separation enhancement, but also perimeter enhancement.

In the embodiment illustrated stereo unit 50 is coupled to left and right speakers 52 and 54 respectively, via respective lines 56 and 58. A differential amplifier 60 is coupled across lines 56 and 58 such that a left minus right differential signal is coupled to a delay unit 62 which delays the signal by an amount described hereinabove. Thereafter, the signals from delay unit 60 is amplified at 64. The signal from the amplifier 64 is applied to a phase splitting circuit 66 which inverts the amplified signal and couples right minus left directional signals to a summing node or mixer 68 interposed in the right channel, and left minus right channel signals into a summing node or mixer 70 interposed in the left channel. A listener 72 having a left ear 74 nearer a left-hand speaker and a right ear 76 nearer a right-hand speaker is located along a central line 78 which defines the midpoints between the left and right speakers.

In operation, the system responds to the signal differential between the left and right channels, delays it by an amount Δ, and in some cases amplifies it at which point it is applied to the phase splitter. By this operation, that which is subtracted from the right channel is the purely directional left channel signal, and that which is subtracted from the left channel is the purely directional right channel signal. It will be appreciated that monaural signals having no left/right information, or signals coming from centre stage which have no left/right information, will be ignored by this system. Thus the central region 80 is one in which the invention has no effect and in which no distortion occurs.

With proper adjustment of the amplifier section of unit 64 sounds coming from the periphery can be made to have a level equal to that of sounds which originated from centre stage. This results in extremely effective stereo image separation and eliminates close to if not all of the cross-mixing of signals from the two speakers at the listener's ears.

Assuming listener 72 is located along the central line, then the amount of delay Δ is established by measuring the distance between the two speakers and by measuring the distance from the left speaker to left ear 74. This ratio establishes the optimum delay via the geometry and if the delay is easily variable as will be discussed, adjustment may be either in accordance with this ratio or when the listener hears maximum separation in the stereo signals.

An alternative method of establishing delay Δ is to measure the angle between lines 84 and 86 to establish the above-mentioned ratio by using the trigonometric relationship.

It has been found that not only is separation enhanced in this distortionless fashion, but also peripheral sound which exists about the perimeter may be artificially enhanced to give an exceedingly pleasing effect of "wrap around" sound. This is accomplished by amplifying the signal from the delay line by an amount in excess of that which corresponds to the level of sound which exists in the central region. This may be increased by as much as ten dB to give the effect of being surrounded completely by the sound. The effect, as noted hereinbefore, is equivalent to having the whole perimeter of the room lined with speakers, each projecting inwardly such that sound is projected as illustrated by arrows 82 towards the center of the room and towards the listener.

It will be appreciated that it is the peripheral sound which is amplified due to the differential signal processing. In short, since monaural or directionless signals are not amplified, it is the signals which have a directionality, either left or right, which are amplified and inserted into the left and right channel speakers.

Referring to Figure 3, an expanded block diagram shows the components of the system of the invention. A differential amplifier 90 performing as a left/right discriminator, is coupled to a left input and a right input. The output of the left/right discriminator 90 is a left minus right signal which is applied to a rumble reducing high pass filter 92, to an anti alias low pass filter 94 and finally to a delay line which a serial-analog delay device. This is basically a bucket brigade device which is clocked via clock 100 under control of a variable control unit 102. The output of delay line 96 is applied to a low pass filter 98 which removes clocking components and lowers the high frequency content to compensate for the different response of the intended and other ear. The resultant signal is then applied to a variable gain amplifier 104 under control of a control unit 106. The output of the variable gain unit is applied to a by-pass switch 110 and thence to a simple phase splitter 112 to generate the left minus right and right minus left correction signals. The output of phase splitter 112 is applied to mixers 114 and 116 respectively in the left and right channel lines. In this embodiment, the output of each mixer is applied respectively to an additional amplifier 120 and 122 which are variable gain amplifiers under control of a master control 124. The outputs of these amplifiers are then applied to external left and right power amplifiers and speakers as illustrated.

It will be appreciated that using the serial analog delay unit for delay unit 96 produces a delay which is continuously variable. The delaying of acoustic signals for ultrashort delay times is not straightforward and has in the past been done with lumped constant elements. These circuit elements provide shifts in phase which are in general fixed in manufacture. Therefore there is no adjustability for listener angle with respect to the speakers.

In the present invention, however, this delay may be continuously varied so that maximum separation for a wide range of listener positions may be achieved. Thus adjustment unit 102 is in effect a

cross-talk cancellation null adjusting unit and may be adjusted via remote control by the listener as he listens to his stereo recordings.

Low pass filter 94 is interposed to take out ultrasonic signals that might beat with the delay clock frequency and high pass filter 92 is interposed so as to remove rumble under 70 Hz. There is in practice very little left/right information below approximately 100 Hz. Thus by providing the high pass filter with a roll-off at 70 Hz, no right/left information or overall bass level is lost in the process. This corrects for rumble which is usually produced by vertical stylus action within the grooves of a record, produced either during recording or reproduction.

Referring now to Figure 4, an embodiment is shown for off-centre listening for a listener who may be located for instance at position 130. An off-centre position may be necessary if it is impossible to locate speakers in the ideal position i.e. allowing the listener to be at a point midway between the speakers. The units 90,92,94,96,98 and 104 of the first embodiment are again employed for each of the channels and are shown by 90',92',94', 96',98' and 104', although a phase splitter is not used to separate the signals to be fed back to the right and left channels. This function is accomplished by duplication of the various units. They function in the same manner and are adjusted as by potentiometers R1 and R2 for a listener located on a centre line at some distance from the speakers as measured along a line perpendicular to the line joining the two speakers.

Variable gain amplifiers 104 and 104' are controlled respectively by potentiometers R3A and R3B to achieve whatever gain is required either for enhancement or for abosulute stereo fidelity.

The outputs of variable gain amplifiers 104 and 104' are coupled respectively to mixers 134 and 134' coupled to the left and right channel lines respectively. The mixers may themselves be amplifiers and their amplitude is adjusted through potentiometers R4A and R4B as illustrated.

Assuming that the listener is off-centre as shown, the output from mixer 134 is applied to a low pass filter 136, to an additional serial analog delay line 138 and thence to a further low pass filter 140 from which point it is applied as the left channel output via switch S1.

Delay 138 is clocked by a clock 142 controlled by potentiometer R5 and typically has a delay greater than or equal to 1×10^{-5} seconds.

The purpose of delaying the left channel signal over the right channel signal is that the off-centre listener is closer to the left channel speakers. Thus he will be receiving signals from the left channel speaker before signals from the right channel speaker arrive. In this manner, the system may be adjusted for off-centre listening with the right channel being provided with the same type of delay unit if the listener is off-centre to the right.

Referring to Figure 5, as has been mentioned hereinbefore, it is with some difficulty that ultrashort acoustic delays are achievable. This is because in standard low noise SAD lines there are 516 different charge transfer elements i.e. the delay line is said to be 516 units long.

In order to use these standard delay units, and with their ultimate limit in clocking frequency, it is possible, to achive shorter delays through using three of these devices.

In this embodiment, analog delay lines 150 and 152 are interposed in the left and right channel lines as illustrated and are clocked identically, for instance, at a clock rate of 128 KHz This gives a 2×10^{-3} second delay for each line. The left and right inputs are also coupled to a differential amplifier 154, the output of which is coupled a third analog delay line 156. This analog delay is clocked at a rate slightly less than delays 150 and 152, for instance at 122 KHz. This provides for a 2.1×10^{-3} second delay such that the overall delay of the left minus right signal with respect to the left and right signals is $.1\times10^{-3}$ seconds. It can thus be seen that relatively short delays can be achieved between any two signals by the use of this differential delay technique.

It will be appreciated that in the embodiment shown in Figure 5, the delayed left or right channel signals and the difference channel may be appropriately mixed to achieve the stereo enhancement.

In general, this technique may be used when it is desirable to delay any one signal with respect to another and the desired delay is too short to be achieved through the clocking of an existing serial analog delay line. In this case, the delays in each of the lines are made different so that the desired delay is obtained as the differential.

Capacitors 158, 159 and 160 are used as low pass filters to remove all clock fundamentals, thereby to avoid clock different frequencies from appearing in the outputs.

This system is useful when bandwidth is not critical, i.e. when the maximum signal frequency is much less than the clock frequency e.g. for short delays at bandwidths less than ⅓ the clock frequency.

CLAIMS

1. Apparatus for a stereophonic audio reproduction system having left and right channel outputs, comprising:

means for deriving a difference signal from signals in said left and right channels;

means for delaying said difference signal; and

a phase splitter coupled to said delay means for phase splitting said delayed signal and coupling the two phase-split phases of delayed signal into said left and right channels so as to subtract delayed left minus right and right minus left components from respectively the left and right channels for enhancing stereo image separation.

2. Apparatus as claimed in claim 1 including an amplifier for location between said delaying means and said phase splitting means for amplifying said delayed signal.

3. Apparatus as claimed in claim 1 wherein said delaying means is variable.

4. Apparatus as claimed in claim 3 wherein said variable delaying means includes a clocked bucket

brigade device.

5. Apparatus as claimed in claim 3 wherein said variable delay means delay is preselected to maximize apparent stereo separation.

6. Apparatus as claimed in claim 1 including an amplifier interposed after said difference signal deriving means for amplifying said difference signal for enhancing perimeter sounds.

7. Apparatus as claimed in claim 1 including means for delaying the signal in one channel after said subtraction to compensate for off-centre listening for that channel, the speaker of which is nearer to the listener.

8. Apparatus as claimed in claim 1 which includes means for delaying the signals in each of the left and right channels by an equal, predetermined amount; means for delaying the difference signal by an amount different from the delay in the left and right channels; means for subtracting the delayed difference signal from the delayed left or right channel signals, for obtaining short delays for the signals in the left and right channels.

9. A method for improving the quality of sound heard from a stereo system having two loudspeakers, one each associated with left and right stereo channels comprising the steps of deriving a difference signal from the signals in the left and right stereo channels, delaying the difference signal, phase splitting the amplified signal, and coupling the phase split signal into the left and right channels so as to subtract delayed left minus right and right minus left components from left and right channels for enhancing stereo image separation.

10. A method as claim in claim 9, wherein the delayed signal is amplified.for enhancing perimeter sounds.

11. A method as claimed in claim 9, wherein the amplification includes amplifying the delayed signal by an amount in excess of directionless signals in the left and right channels as they come from the stereo system.

12. A method as claimed in claim 11, wherein the delay in the delaying step is variable and is preselected so as to effect maximum stereo separation for the listener.

13. A method as claimed in claim 9 including delaying the signals in one of the channels after the subtracting step by an amount to compensate for off-centre listening, the delay being provided for the channel having the corresponding speaker nearer to the off-centre listener.

14. A method as claimed in claim 9, including delaying the signals in each of the left and right channels by an equal, predetermined amount, delaying the difference signal by an amount different from the delayed left or right channel signal, and subtracting the delayed difference signal from a delayed channel signal, in order to obtain short delays for the signals in the left and right channels.

15. A method of obtaining short delays with clocked bucket brigade devices, comprising the steps of delaying one signal with a bucket brigade analog delay line clocked at one clocking rate, delaying another signal with a second bucket brigade analog delay line clocked at a different rate to that of the other delay line and combining the delayed signals so as to obtain a delay which is the difference in delays engendered by the different clocking rates.

16. A method according to claim 15 wherein the clocking rates are significantly higher in frequency than the frequency of any information on the signal.

17. Apparatus for obtaining short delays of a signal with clocked bucket brigade devices, comprising means for delaying said signal with a bucket brigade analog delay line clocked at one clocking rate, means for delaying a reference signal with a second bucket brigade analog delay line clocked at a different rate, and means for combining the delayed signals so as to obtain a signal delayed by the difference in delays engendered by the different clocking rates.

18. Apparatus according to claim 17 wherein the clocking rates are significantly higher in frequency than the frequency of any information on said signal.

New claims or amendments to claims filed on
New or amended claims:-
New claims 19 to 22 inclusive to follow original claims 1 to 18 as on attached sheet.

19. A stereophonic audio reproduction system constructed and arranged as herein described with reference to and as illustrated in Figures 2 and 3 of the drawings.

20. A stereophonic audio reproduction system constructed and arranged as herein described with reference to and as illustrated in Figures 2 and 4 of the drawings.

21. A stereophonic audio reproduction system constructed and arranged as herein described with reference to and as illustrated in Figure 5 of the drawings.

22. Apparatus for obtaining short acoustic delays constructed and arranged as herein described with reference to and as illustrated in Figure 5 of the drawings.

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